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Environmental impacts of the life cycle of alluvial gold mining in the Peruvian Amazon rainforest

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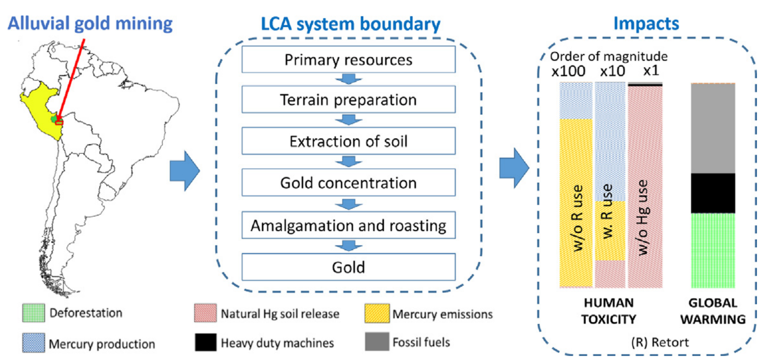
HIGHLIGHTS

- Informal gold mining is rampant in many areas of the Peruvian Amazon.
- Environmental impacts of gold mining in the Amazon have been analyzed using LCA.
- Over 80% of human toxicity linked to mercury emissions in gold recovery activities.
- Mercury recovery and gravimetric tables considerably reduce human toxicity impacts.
- Deforestation in mining activities has a major contribution to climate change.

GRAPHICAL ABSTRACT



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ABSTRACT

Alluvial gold mining activities in the Peruvian Amazon rainforest are responsible for mercury emissions and deforestation. To understand related environmental impacts, specifically toxicity and climate change, this study uses Life Cycle Assessment methodology. Four predominant extraction systems were selected and modelled and three scenarios that reflect currently available gold recovery systems were modelled: amalgamation, amalgamation with mercury recovery through retort system and gravimetric tables. The USEtox and IPCC life cycle impact assessment methods were used to assess the environmental impacts in term of human toxicity, freshwater ecotoxicity and climate change.

Results show that for all systems, human toxicity values are governed by mercury emissions in gold recovery activities (ca. 80%). However, the use of retort significantly lowers these impacts (ca. 90%). Machines and diesel use for ore extraction and freighting activities drive freshwater ecotoxicity. Moreover, deforestation has a major contribution on the environmental impacts related to climate change. However, these impacts are dependent on the type of extraction system. Although human toxicity, freshwater ecotoxicity and climate change are frequently studied separately, a direct relationship between them has been identified in this system. Finally, beyond the environmental burdens related to alluvial gold mining, there are impacts affecting the social, cultural, and economic dimensions that will need to be analyzed to ensure a comprehensive understanding of the system.

1. Introduction

Through history, resource extraction has been an important activity for the development of humanity. Different cultures, stimulated by a variety of adversities, have learned multiple extraction techniques to use

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these resources in their daily life. For instance, metals have been a key element in the development of the early technosphere in many ancient civilizations, including the Egyptians or the Incas (Habashi, 2005; Petersen, 2010). Moreover, mining of cinnabar (HgS), from which mercury is obtained, and its use for the conservation of human bones has been reported during the Later Stone Age (Parsons and Percival, 2005), and the use of amalgamation techniques to recover silver has been used in Latin America for more than 400 years (Beal et al., 2013). Coal, once named by the Romans the "best stone in Britain", was initially appreciated as jewelry and later as a fuel, triggering the Industrial Revolution (Freese, 2016).

Over time, the development and adoption of technology in the extraction processes and the growing demand for resources by society has augmented the extraction rate exponentially, triggering landscape changes and environmental impacts (Reed, 2002). For instance, deforestation for timber is a notorious example of the growing demand of this natural resource, producing significant landscape changes to address, in part, urban expansion, while degrading the natural environment. In addition, this rapid augmentation in the use of resources has generated an overall dissimilarity within the extraction sector. This is the case of gold mining activities around the world, as these can be performed by artisanal miners or transnational companies. Moreover, gold extraction processes, resource use, yield and grade of mechanization can vary considerable depending on their type and size. While micro artisanal mining is a central activity for families around the world and uses mainly manual tools, small, medium and large mining activities may include mechanized processes, generating a greater landscape change (Veiga and Hinton, 2002).

In recent decades, artisanal and small-scale gold mining (ASGM) has grown considerably around the world (e.g., Brazil, Peru, Colombia, Venezuela, Costa Rica, Ghana, French Guiana, Indonesia, Zimbabwe) (Green et al., 2019; Arifin et al., 2015; Doering et al., 2016; Grimaldi et al., 2015; Kristensen et al., 2014; Rajaee et al., 2015; Telmer and Veiga, 2009). This phenomenon is especially attributable to the rising prices of metals and the global economic crisis, creating a new gold rush and doubling the workforce involved in this activity (Seccatore et al., 2014). In the particular case of Peru, gold mining has experienced a notable expansion in the past three decades. This led to an estimated 40 metric tons of artisanal gold production in 2012 (Seccatore et al., 2014). For example, in Madre de Dios (MDD), an important mining region located in the southern Peruvian Amazon, gold mining has consolidated as the main economic activity (Chique et al., 2013). In fact, according to Asner et al. (2013), between 1999 and 2012, the geographic extension of gold mining in MDD increased by ca. 400%, leading to significant environmental, social and cultural implications. Moreover, the region has seen a population increase of 31% mainly due to migration from other areas in Peru between 2007 and 2017 (INEI, 2018). Similarly, deforestation, mercury contamination, and human trafficking issues have arisen and are associated with certain gold mining activities (Arriarán and Chávez, 2017).

According to the Peruvian Forestry Information System (SNIFFS), between 2001 and 2016 approximately 8% of the deforested Peruvian Amazon rainforest area occurred in MDD, mainly due to agricultural, logging and mining activities (SNIFFS, 2017). Asner and Tupayachi (2017) and Caballero Espejo et al. (2018) confirmed the rapid increase in deforestation and expansion linked specifically to mining activities in the region. The results estimated by Asner and Tupayachi (2017) indicate that more than 3900 ha per year were lost due to alluvial mining in MDD during the period 1999–2016 equivalent to a cumulative deforested area of approximately 60,000 ha. Similarly, Caballero Espejo et al. (2018) estimated around 100,000 ha when the period 1984–2017 was evaluated.

Besides deforestation, mining activities generate disturbances in local ecosystems and urban areas. For instance, there is evidence of mercury biomagnification in fish and other fluvial animals, namely, long-whiskered catfish or *dorado* (*Brachyplatystoma rousseauxii*), which is widely consumed in MDD (Ashe, 2012; CAMEP, 2013; Deza Arroyo, 1996; Roach et al., 2013). In a different ecosystem (i.e. Lake Titicaca) but also linked to gold mining activities, Gammons et al. (2006) discovered high levels of mercury in indigenous catfish (*Trichomycterus* spp.). Concerning urban air pollution related to artisanal gold mining, Cordy et al. (2011) found high mercury levels in five cities of Antioquia (Colombia) due to amalgam roasting in gold processing centers. Furthermore, mercury concentrations in human hair in adults that reside in MDD, specifically Puerto Maldonado, were found to be higher than the reference limit of 1 ppm recommended by the US Environmental Protection Agency (CAMEP, 2013). Mercury use has traditionally been linked to artisanal gold mining and, while funds have been allocated to uncover ways to reduce its use and mitigate its impacts (e.g. educational initiatives), in the past these have been unsuccessful (Hilson, 2006). "Novel and comprehensive strategies" could successfully address this issue in the future (Zolnikov and Ortiz, 2018).

While there is a clear qualitative understanding of the probable environmental impacts related to informal gold mining, quantifying these impacts has not been an easy task, especially when related to the fate and transport of mercury, mainly due to knowledge gaps regarding its speciation in the environment (Reis et al., 2016). In terms of life cycle approaches, Valdivia and Ugaya (2011) performed a life cycle inventory of ASGM activities in Peru, including alluvial mining. However, this study did not include any assessment or quantification of the environmental impacts. Moreover, despite the fact that Life Cycle Assessment (LCA) has been used to assess large scale mining activities (Ferreira and Leite, 2015; Góralczyk and Kulczycka, 2005; Norgate and Haque, 2010), only one recent study that considers ASGM in the Philippines has been identified in the literature. The latter, by Cenia et al. (2017) targeted greenhouse gas (GHG) emissions and energy use and focused on different technical conditions and gold formations (Cenia et al., 2017). In this sense, the main objective of this research is to quantify the life cycle environmental burdens in terms of climate change and toxicity of alluvial mining in the Peruvian Amazon, specifically MDD, for four typical extraction systems utilizing LCA. Deforestation and mercury use are closely associated with alluvial gold mining in MDD. Thus, a thorough analysis of climate change and toxicity are highly relevant for this system. The uniqueness of the studied area, the Peruvian Amazon rainforest, the life cycle perspective, the assessment of four modelled gold extraction systems, which is repeatedly omitted by policy makers, and the selection of impact categories, make this study an important contribution for policy support and academia. LCA and the followed methodological workflow are presented in chapter two, as well as the description of the studied area. Finally, the main results, their discussion and a set of recommendations are provided.

2. Materials and methods

2.1. Goal and scope of the analysis

The main goal of the study is to analyze the environmental impacts; namely, human toxicity, freshwater ecotoxicity and climate change, related to the extraction of gold from alluvial deposits in MDD. More specifically, as shown in Fig. 1, the study focused on Huepetuhe (12°59′43″ S; 70°31′37″W), a mining area located between the Colorado, Inambari and Madre de Dios rivers and that has a long history of gold mining activity, and Laberinto, a series of mining concessions located along the Madre de Dios river and that have as main alluvial port, Puerto Rosario de Laberinto (12°43′05″S; 69°35′12″W). Alluvial mining in other locations was not included, although, based on the interviews, the general extraction processes are reported to be very similar. Ongoing mining in illegal areas, such as the mining site named La Pampa, located in the buffer zone of the Tambopata National Reserve, were not studied mainly because mining activities in these areas are classified as "illegal"

and a particular tension exists that would jeopardize the safety of the research team and participants (Arriarán and Chávez, 2017; Clavel, 2016).

LCA has been selected as the methodological framework to evaluate the environmental impacts of alluvial mining in the Peruvian Amazon (ISO, 2006a). This holistic environmental assessment tool has been broadly used in the past to analyze different systems worldwide, such as agriculture, civil infrastructure, waste to energy systems, and electronic equipment, among others, but also increasingly in the Peruvian context (Kahhat et al., 2009; Margallo et al., 2014; Quispe et al., 2019; Vazquez-Rowe et al., 2016; Williams, 2004). More specifically, this study followed the ISO 14040 and 14044 standards that propose the use of four main stages: scope and goal definition, inventory analysis, impact assessment, and interpretation (ISO, 2006a, b).

The function of the system is the extraction of gold from alluvial ores and processing up to a state adequate enough to be sold at gold shops. The final amalgam roasting is usually performed by gold dealers in Huapetuhe, Puerto Rosario de Laberinto and other surrounding villages (see Fig. 1). While this study excludes from the analysis the transportation of gold from the mining site to the gold shop and activities performed in the latter, the final roasting is included, due to the importance of this process in the system. Therefore, the functional unit (FU) was defined as 1 kg of gold ready for sale.

Fig. 2 presents the general processes related to gold extraction in the area, as well as the overall system boundary of the system. Once the required goods and equipment (e.g. mercury, polymers, etc.) are received at the mining area, the preparation of the terrain initiates. The following process includes: extraction of soil/mud, gravitational processes, gold recovery using amalgamation techniques to separate gold from alluvial formations, and, in some cases, mercury recapture. Direct and indirect emissions to the environment related to each phase and relevant to the selected impact categories are included. A more detailed description of the processes is explained in the Supplementary data section. Finally, inappropriate practices, such as oil leaking, plastic littering, among others were not included in the analysis.

2.2. Description of the system

Four extraction systems were identified and analyzed. Table 1 presents the classification and main characteristics of alluvial auriferous extraction systems. Despite the overall similarities, important differences persist, such as differences in terms of yields, resource consumption, machinery use (e.g. dredges, excavators), and operation sites (e.g. river based versus piedmont). These gold extraction processes are typical, technologically precarious, and in general terms similar throughout the region. A more detailed description of the four extraction systems for alluvial gold mining in MDD is explained in the Supplementary data.

2.3. Data acquisition

The mining areas of Huapetuhe and Laberinto, the core areas analyzed, were visited in June 2017 and July 2018. Three main steps have been followed in order to gather the required foreground data for the project: (a) questionnaires that were used in semi-structured interviews with miners, engineers and experts on alluvial mining; (b) field studies, site observations, video and photo audits; and (c) a thorough literature review. The questionnaire covered the most important processes related to the extraction of gold from alluvial deposits. The selection of miners, engineers and experts for the interviews followed a non-probabilistic sampling procedure given the existing tensions between miners and the government and other sectors (Cuzcano Torres, 2015;

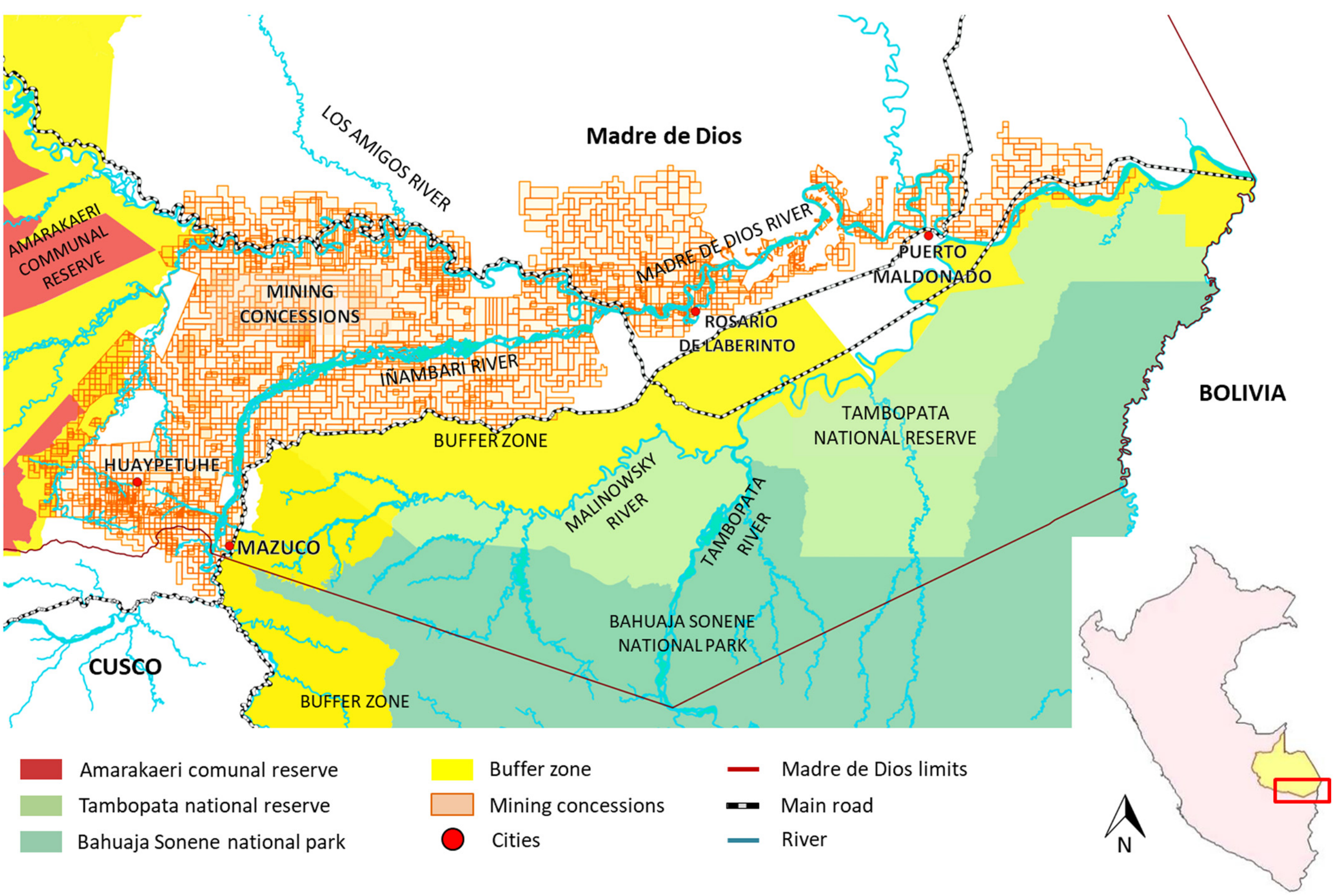

Fig. 1. Location of the area of study within the Peruvian Amazon showing alluvial gold mining zones and Natural Reserves and Natural Parks.

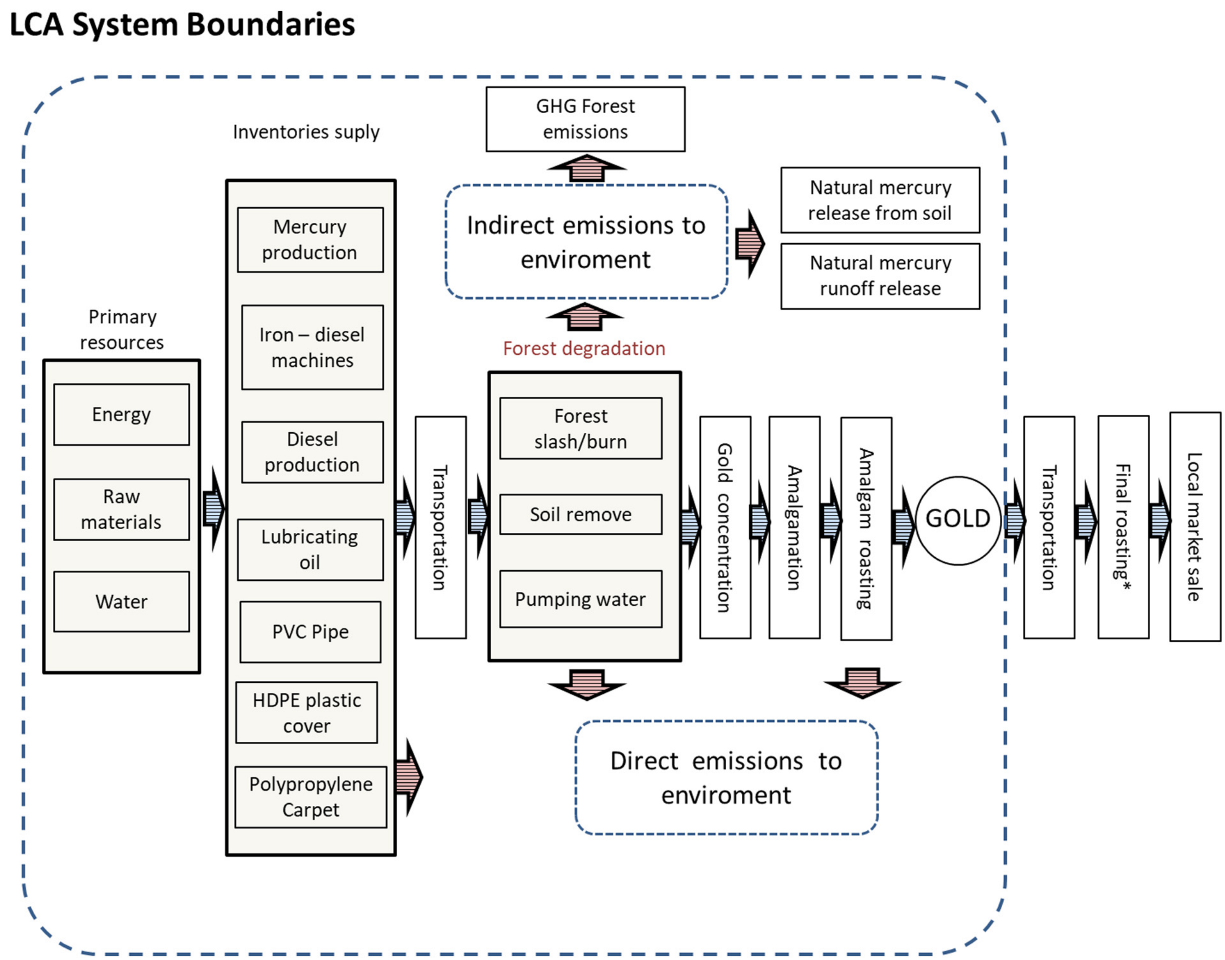

Fig. 2. Schematic representation of the system boundary for alluvial gold mining. (*Final roasting has been included in the analysis).

GOMIAN, 2015). For this same reason, and given the reticence of miners, the diversity of mining activities, the high variability in the use of resources, machinery characteristics, the ore grade extracted and others, this research heavily relied on site-specific observations, video and picture audits, as well as engineering calculations to model all the processes used in alluvial mining activities. Furthermore, plausible ranges for the most relevant variables, as shown in Table 2, have been used for the life cycle calculations and, thereafter, used for the scenario analysis. Technical reports and other related material were used. Finally, background data for mercury extraction, or the production of machinery, fossil fuels or plastics were obtained from the ecoinvent database v3.3 (Wernet et al., 2016).

2.4. Data modeling and methodological assumptions

The estimated range for gold extraction yields was calculated according to the profitability of each extraction process, volumes of earth moved, interviews with mining producers and literature. The average amount of gold extracted by ASGM in MDD soils has been documented by several authors, varying from 0.1 to 1 g/m^3. In the case of mercury, the typical value in the amalgamation process is 2 g of elementary mercury per gram of gold. However, the literature review, as well as the results from the interviews showed that this value may range from 1 to 5 g, as shown in Table 2.

No reliable sources have been identified regarding the percentage of miners using retorts for the first amalgam roasting. Some authors have reported higher acceptance of retorts by miners, as high as 50% (Mosquera et al., 2009). Nevertheless, based on the interviews and site visits, it was observed that, contrary to governmental expectations, there has been a low penetration of this technology in the informal mining system. Consequently, this study uses an adoption rate that ranges between 5% and 15%. We believe that some reasons behind the low adoption rates include little awareness from informal and illegal miners related to occupational and global risks, and negative perception from buyers regarding the gold obtained from retort systems (possibly due to a whitish gold product as an outcome of a poorly sealed retort). Regarding mercury recovery, we assumed that the retort system recovers between 85% and 95% of the mercury contained in the amalgam. This range was obtained from other studies identified in the literature (see Table 2).

In addition, rural air emissions of mercury without the use of retort range between 50% and 90% (Londenius and Malm, 1998; Pfeiffer and Larceda, 1988). The remaining mercury is later roasted in gold shops, where the retort system is mostly used. This study estimates a range of 2% to 10% emissions of mercury to urban air. Furthermore, range emissions to soil - water environment range between 10% and 40% (Londenius and Malm, 1998; Pfeiffer and Larceda, 1988). The estimated range for natural Hg content in soils ranged from 20 to 4000 ng/g based on the literature, as shown in Table 2.

2.5. Cycling of mercury and ASGM

Mercury is present in the environment in different inorganic and organic forms, such as metallic mercury, Hg^0; mercuric, Hg(II) or methylmercury, CH_3Hg. The human- and ecotoxicity of this element depends on the intrinsic chemical and physical characteristics of each of its forms, its fate and transport in the environment, exposure pathways, and others (ATSDR, n.d.; Clarkson and Magos, 2006; Driscoll et al.,

Table 1
Classification and main characteristics of alluvial auriferous extraction systems (based on field studies and from Bocanegra-Davila, 2004; Cabanillas Vásquez, 2016; Mosquera et al., 2009).

System description		Extraction system			
		I	II	III	IV
		Minimum deforestation, manual tools and low production	High deforestation, medium production, mud suction	No deforestation and mud suction from riverbeds	Medium to high deforestation, intensive production
Main type of tools or machines	Manual tools	X			
	Use of water pumps	X	X	X	X
	Use of dredgers (mud suction)			X	
	Use of heavy duty machinery				X
Area of operation	Alluvial plain	X	X	X	
	Riverbanks		X		
	Riverbeds			X	
	Others	X			
	Piedmont	X	X		X
Production rate	Low	X			
	Medium		X	X	
	High			X	X
Deforestation[a]	No deforestation	X	X	X	
	Low deforestation	X	X		
	Medium deforestation		X		X
	Intensive deforestation				X
Local names for extraction systems	*Carretilla*	X			
	Canaleta	X			
	Ingenio	X			
	Chupadera		X		
	Traca		X		
	Chupadera/traca		X		
	Carranchera			X	
	Balsa gringo/castillo			X	
	Draga			X	
	Chute				X

[a] Assuming first land intervention.

2013; Rice et al., 2014). Once emitted, metallic mercury has a lifetime in the atmosphere that may range from a few months to around 1 year allowing long distance transport before wet and dry deposition to land and water bodies (Driscoll et al., 2013; Selin, 2009). Oxidation of atmospheric Hg^0 forms Hg(II), which has a shorter lifetime in the atmosphere: from hours to days (Driscoll et al., 2013). After deposition, Hg (II) can revolatilize, accumulate in ecosystems, converted by microorganisms into methylmercury or aquatic systems (Selin, 2009). Methylmercury, a major neurotoxin, has low solubility in water, which eases its assimilation by organisms. It tends to bioaccumulate in fish and other aquatic organisms. Thereafter, it enters the human food chain through bioamplification, becoming a major source of exposure for humans (Rice et al., 2014).

In recent decades, especially after the severe human health problems detected in Minamata (Harada, 1995), special attention has been placed to understand and mitigate human health and environmental impacts related to mercury and mercury compounds. The most notorious and significant effort is the recently enforced (i.e. 2017) Minamata

Table 2
Ranges for the most relevant parameters utilized in the life cycle analysis of the alluvial mining system in Madre de Dios.

Description	Units	Minimum	Maximum	Typical	Source
Gold extraction yields	g/m^3	0.1	1	0.3	(Mosquera et al., 2009; Alvarez et al., 2011; Valdivia and Yauri, 2006; Kuramoto, 2001; Moschella Miloslavich, 2012).
Mercury to gold ratio use for amalgamation	g Hg/g Au	1	5	2	(Amouroux et al., 1999; Dominique et al., 2007; Green, 2017; Mosquera et al., 2009; Pirrone and Mason, 2009; Roulet et al., 1998; Telmer and Stapper, 2012a, b; Telmer and Veiga, 2009; Valdivia and Yauri, 2006; Winsemius et al., 2018).
Miners using mercury recovery systems (i.e. retort)	%	5	15	NA	Not available. Estimated based on interviews. Some authors have reported higher acceptance of retorts by miners, as high as 50% (Mosquera et al., 2009).
Recovery of mercury content in amalgam, with retort	%	75	95	90	(Valdivia and Yauri, 2006; UNEP, 2013; Telmer and Stapper, 2012a, b).
Mercury emissions to rural air (without use of retort)	%	50	90	65	(Londenius and Malm, 1998; Pfeiffer and Larceda, 1988).
Mercury emissions to rural air (with use of retort)	%	2	10	5	(Londenius and Malm, 1998; Pfeiffer and Larceda, 1988).
Mercury emissions to soil and water environment	%	10	40	30	(Londenius and Malm, 1998; Pfeiffer and Larceda, 1988).
Mercury content in soils and sediments	ng/g	20	4000	240	(M Roulet et al., 1998; Fadini and Jardim, 2001; Moreno-Brush et al., 2016; Veiga et al., 2006; Lechler et al., 2000; Diringer et al., 2015).
Potential Hg soil release	%	20	100	50	Estimated
Potential natural Hg release from soil	ng/g	48	240	150	Calculation based on natural mercury content in soils and potential release
Deforestation CO_2 emissions	t CO_2 eq/ha	–	–	510	Based on reference level of forest emissions for MDD and its corresponding deforested area for 2001–2014 period, content in (MINAM, 2015)

Convention that has as main objective the protection of society and the environment from its anthropogenic emissions (Selin et al., 2018; UN-Environment, 2017). Anthropogenic atmospheric mercury emissions are linked to human activities that have been performed for thousands of years. In the past two centuries, these emissions have been predominantly associated to gold and silver mining, as well as mercury production, the later used in the former activities (Driscoll et al., 2013; Streets et al., 2011). Other activities where mercury is used include the production of lead and zinc and the use of coal as a primary energy source (Zhang et al., 2016). The fate of these emissions is unclear, but part of the natural mercury stock could be associated to anthropogenic emissions (Driscoll et al., 2013).

Currently, worldwide ASGM is considered a major user of mercury (Streets et al., 2011). Global annual mercury emissions to the environment, due to ASGM, were estimated to range between 640 and 1350 metric tons, of which ca. 35% are emissions to the atmosphere (Telmer and Veiga, 2009). Amalgamation, the process that follows gold concentration, requires elementary mercury to bind gold. The subsequent process, amalgam roasting, burns the gold-mercury amalgam and generates gaseous mercury releases to the environment and becomes a major source of mercury exposure for miners through inhalation. Exposure from miners and surrounding human communities may represent acute and long-term health problems, such as neurological and kidney health impacts (Gibb and O'Leary, 2014; Kristensen et al., 2014). A global health impact related to chronic metallic mercury vapor intoxication or CMMVI among artisan and small gold miners was estimated to be between 1.22 and 2.39 million DALYs (Disability adjusted life years) (Steckling et al., 2017). Interestingly, however, some mining activities around the world have incorporated retorts, reducing a major part of the gaseous mercury emissions generated while roasting the amalgam: more than 95% reduction if used properly (Veiga and Hinton, 2002). In fact, after condensation, recovered mercury could be reused in the amalgamation process. Unfortunately, retort has not been extensively adopted by miners around the world.

Moreover, mercury may be released into the environment as a result of soil erosion due to increased runoff in deforested areas related to mining or other anthropogenic activities (Lechler et al., 2000; Roulet et al., 2000; Veiga, 1997) due to high natural accumulation of mercury in the environment (Fadini and Jardim, 2001; Roulet et al., 2000). Soil erosion and leaching of transformed land was shown to be an important mercury source for local aquatic systems where the formation of methylmercury is a major concern for humans (Lechler et al., 2000; Roulet et al., 2000). Findings of important mercury values associated with the fine particles of the sediments carried by rivers from the mining activity zones (Moreno-Brush et al., 2016) are an indicator that mercury naturally contained in the soil, released and washed during the auriferous extraction process may also be an important source of mercury in the environment. Moreover, regardless the origin of mercury in streams, Green et al. (2019) found a direct correlation between the content of organic material in sediments and mercury in southern Zimbabwe. Fig. S1 presents the potential of mercury liberation from soil as a consequence of removal and washing could compared to systems emissions to soil and water.

2.6. Life cycle inventory

A classification and summary of the main characteristics of the extraction systems has been previously provided in Table 1. Table 3, in contrast, refers the inputs and outputs of the gold mining systems to the selected FU (i.e. 1 kg of gold ready for sale). Although temporal correlation is not expected to affect the results, other than technological leaps that may occur in the future, the life cycle inventory is representative for years 2017 and 2018. Concentration of gold in the sediments will be a main carrying factor rather than interannual variability.

2.7. Life cycle impact assessment

Considering the highly specific characteristics of the system analyzed (i.e. mercury pollution and global warming potential due to deforestation), as well as the social and political concerns involved, the LCIA methods selected were USEtox and IPCC, 2013 to analyze toxicity and climate change, respectively. In this sense, it should be noted that both methods have been identified as the preferred methodological options to compute environmental burdens (Hauschild et al., 2013; Jolliet et al., 2018). On the one hand, USEtox has been formulated to specifically characterize the impacts of chemicals to human health and freshwater ecotoxicity (USETox 2.0). This impact assessment method is based on scientific consensus and was motivated, in part, due to the

Table 3
Inputs for alluvial gold extraction in the Peruvian Amazon Forest to produce 1 kg of gold.

Type of extraction system *e.g. Types* Description		Units	I: Carretilla	II: Chupadera/traca	III-A: Caranchera	III-B: Dredge	IV-A: Partial chute	IV-B: Complete chute
System gold yield (Min-Avg-Max)		g/m^3	3–3.6–5	25–30–40	7–9–10	30–40–60	30–51–80	95–162–200
Iron pumps maintenance (iron component replacement)	Heavy duty machinery and replacement components	kg	–	8.9	17.8	8.3	–	–
Pumping system powered by diesel engines		kg	43.2	10.7	37.0	17.9	9.4	2.8
Heavy machines (digger and front loader)		m^3	–	–	–	–	3333	3333
Dump trucks (15 m^3)		m^3	–	–	–	–	–	3333
Diesel		kg	2625	3779	4199	2507	4940	2955
Lubricating oil	Fossil fuels	kg	83.2	33.5	7.4	42.7	31.9	33.4
PVC pipe		kg	111.1	22.2	44.4	12.4	13.1	4.1
Plastic film		kg	212.5	25.5	99.2	22.2	17.5	11.0
Polypropylene rug	Polymers	kg	19.4	4.7	10.4	3.5	3.4	2.2
Water/land								
Water use, river, PE		m^3	100,000	66,667	100,000	150,000	50,000	50,000
Forest transformation		m^2	–	1111	–	–	667	417
Elemental mercury use	amalgamation	kg	2.00	2.00	2.00	2.00	2.00	2.00
Elemental mercury emissions								
Urban air		kg	0.10	0.10	0.10	0.10	0.10	0.10
Rural air		kg	1.30	1.30	1.30	1.30	1.30	1.30
Natural soil		kg	0.30	0.30	0.30	0.30	0.30	0.30
Freshwater ecosystem		kg	0.30	0.30	0.30	0.30	0.30	0.30
	Min.	kg	0.23	NA	0.23	0.23	0.23	0.23
Potential natural Hg soil release	Max.	kg	1.36	NA	1.36	1.36	1.36	1.36

high uncertainty when analyzing toxicity of chemicals in other impact assessment models (Hauschild et al., 2013). The characterization factors of USEtox are divided into carcinogens and non-carcinogens impacts, as well as the sum of both, to account for chemical emissions to air (e.g. urban or rural), water (e.g. freshwater and seawater) and soil (e.g. natural or agricultural). Thereafter, these are used to report environmental impacts in two main categories: freshwater ecotoxicity and human toxicity. It is important to note, however, that there are still some limitations related to the use of USEtox, as there is a double classification of substances due to its "relatively high uncertainty of addressing fate and human exposure" (Rosenbaum et al., 2008). Thus, characterization factors of substances are classified as recommended or interim (Rosenbaum et al., 2008). Mercury, due to its complex fate and transport mechanisms, is part of the interim substance subgroup. Despite these limitations, the combined use of recommend and interim USEtox models, as performed in this study, is preferred (Golsteijn, 2014) and scientific studies have proved its usefulness when dealing with human toxicity and ecotoxicity footprints on a national level (Nordborg et al., 2017; Sörme et al., 2016). On the other hand, IPCC, 2013, the leading single impact assessment method for climate change was used to quantify the impacts related to GHG emissions (IPCC, 2013). The selected time horizon was 100 years. SimaPro v8.4 was the software used to carry out the computation of the results (PRé Consultants, 2018).

2.8. Scenario analysis

There are three possible technologies available in the study area for gold recovery and regardless the rate of adoption of each one is important to assess their impacts in the system. Thus, the following three scenarios were modelled in this LCA study (i) Scenario A: amalgamation without use of retort, (ii) Scenario B: amalgamation with the use of retort, and (iii) Scenario C: impacts excluding mercury emissions from the amalgamation process.

3. Results

3.1. Results per scenarios

Table 4 and Fig. 3 present the average results for human toxicity, fresh water ecotoxicity and climate change for the studied extraction systems and the relative contribution of each process of the system. Results show that for all systems, human toxicity values are governed by mercury emissions related to gold recovery activities, as well as mercury ore extraction. Moreover, the total displacement of mercury within the system suggests that altered natural stocks of mercury due to soil removal could be, under certain conditions, as relevant as mercury use in the system. In fact, deforestation is a major consequence of these activities and is generated due to direct (i.e. mining activities) or indirect (e.g. access to the mining area) impacts, depending on the type of mining system. Besides, deforestation has a major contribution on the environmental impacts related to climate change and represents on average around 40% of total impacts, as shown in Fig. 4. Freshwater ecotoxicity is driven by diesel consumption, freighting activities and machinery use. It is important to note, however, that there is a knowledge gap related to the impact of mercury in terms of freshwater ecotoxicity. Hence, this could be potentially reflected in the current characterization factors for this impact category.

While human toxicity is mostly driven by mercury use in the amalgamation process (80% as shown in Scenario A), the use of retort and subsequent reuse of mercury (Scenario B) could reduce significantly the importance of this process (i.e. amalgamation) in the system and the overall impacts (e.g. from 1.92E−02 to 2.06E−03 cases in the human toxicity, cancer, category). This is mainly due to lower mercury emissions to the atmosphere because of amalgam roasting and the reduction of mercury utilization due to its recovery in the retort, after re-activation. Moreover, if mercury is completely avoided in the gold extraction process (i.e. Scenario C that represents the use of gravimetric table in the gold recovery process), a greater mitigation of human health impacts (i.e. 99%) is achieved. Despite the avoidance of mercury in gold extraction systems, it is important to state that this element may still be responsible, to a lesser extent, for the toxic effects on human health, due to the potential release of mercury naturally contained in the soil.

3.2. Results per gold extraction system

Figs. 4, and S2, S3 and S4 of the Supplementary data, presents the life cycle environmental impacts for the most representative gold extraction types and gold production ranges. The scale of these impacts is shown in Fig. 5 and depicts the relevance of the use of mercury and deforestation in human health impacts and deforestation, respectively. Concerning deforestation (Fig. 4), Type IV and one Type II extraction systems (i.e. *chupadera/traca*) are those linked to medium or intensive deforestation in the initial land intervention. However, while Type II systems have a more nomadic pattern, Type IV systems show an opposite behavior. Moreover, the high variability in alluvial mining activities in MDD is evident in the extraction systems and gold production rates. The greater the gold production rate of the systems, the lower the environmental impacts. However, unique characteristics of the extraction system are also relevant. For instance, if the use of mercury for gold recovery is excluded from the assessment, Type II and III systems present the lowest environmental impacts concerning human toxicity and freshwater ecotoxicity (Figs. S2, S3 and S4). In addition, Type III systems also present the least impacts for climate change.

4. Discussion

The main objective of this research was to expand the understanding on the life cycle environmental impacts of alluvial mining in the Peruvian Amazon in MDD and to provide policy makers with additional information that could be used to support well-informed decisions. Results from this research study assert that human toxicity consequences over the life cycle of alluvial mining activity in MDD are highly dependent on the use of mercury from the technosphere. Scenarios that consider the use of retort or, especially, the avoidance of mercury due to the use of gravimetric tables, present clear improvements in terms of human toxicity. Thus, we recommend the inclusion of these strategies as part of a package of integral solutions to the alluvial mining system in MDD. However, while the avoidance of mercury for the amalgamation process may lower human health risks, the activity itself will continue to jeopardize the environment with this hazardous element. Thus,

Table 4
Impacts of ASGM for gold extraction system average composition for the FU = 1 kg of gold (calculated based on the average yield of each extraction systems, as seen in Table 3).

Impact category	Units	Scenario A	Scenario B	Scenario C
		Amalgamation Hg/gold = 2	Considering retort use	Avoiding mercury use
Human toxicity, cancer	Cases	1.92E−02	2.06E−03	4.41E−04
Human toxicity, non-cancer	Cases	2.23E+00	2.10E−01	1.89E−02
Freshwater ecotoxicity	$PAF \cdot m^3 \cdot day$	5.65E+06	5.61E+06	5.58E+06
IPCC GWP 100 years	kg CO_2 eq	3.10E+04	3.10E+04	3.10E+04

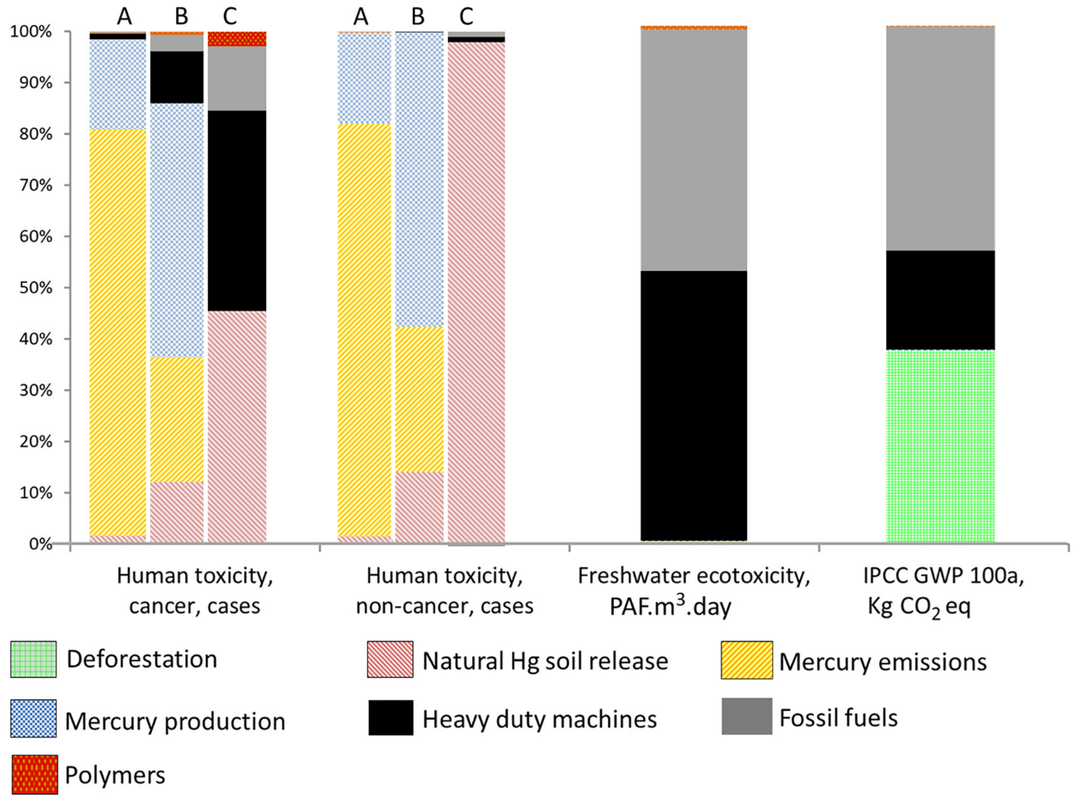

Fig. 3. Relative environmental impacts for each scenario of gold production in the Peruvian Amazon rainforest. (Scenario A: amalgamation without use of retort, Hg/Au = 2; Scenario B: amalgamation with the use of retort; Scenario C: impacts excluding mercury emissions from the amalgamation process. Calculated based on the average yield of each extraction systems, as seen in Table 3). Note: Freshwater ecotoxicity and climate change are not dependent on the use of mercury, thus, no scenarios are required.

interventions in the system should not only focus on phasing out mercury in informal mining, but also on mitigating the release of "natural" stocks of mercury in the Peruvian Amazon.

Depending on the extraction system, significant landscape changes are tightly associated to alluvial mining, especially the ones related to deforestation. These impacts are augmented due to the unique

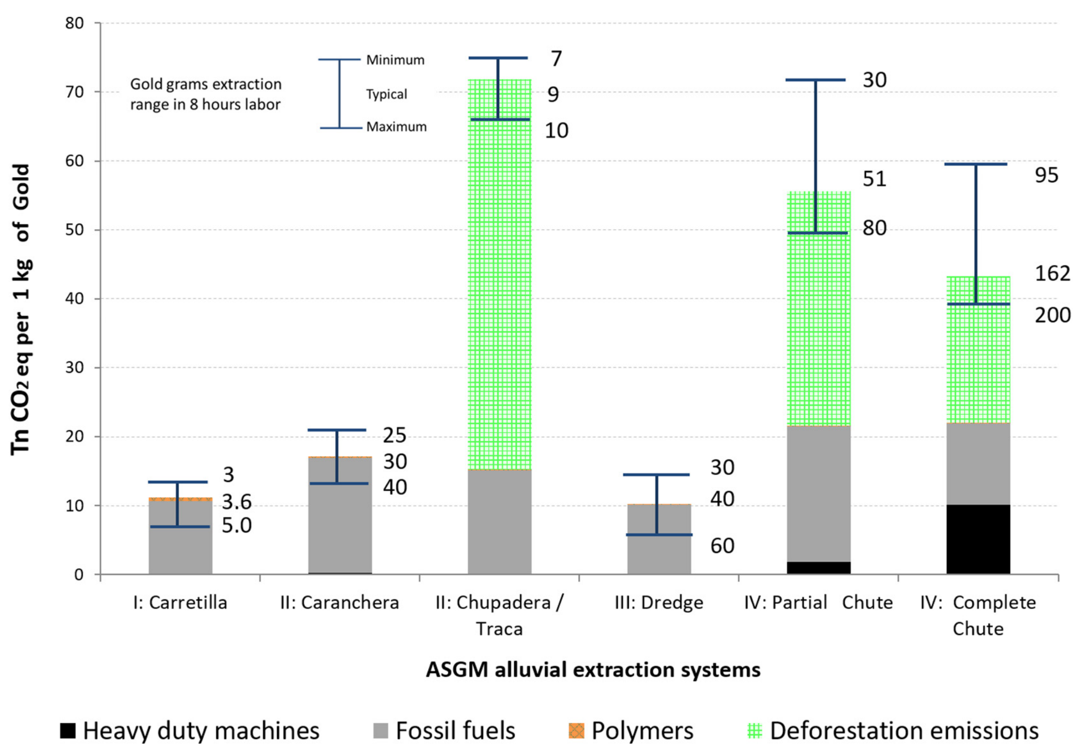

Fig. 4. Global warming potential for the most representative gold extraction types based on gold production ranges: I-Carretilla; II-Chupadera/traca; III-A-Caranchera; III-B-Dredge; IV-A-Partial chute; IV-B-Complete chute.

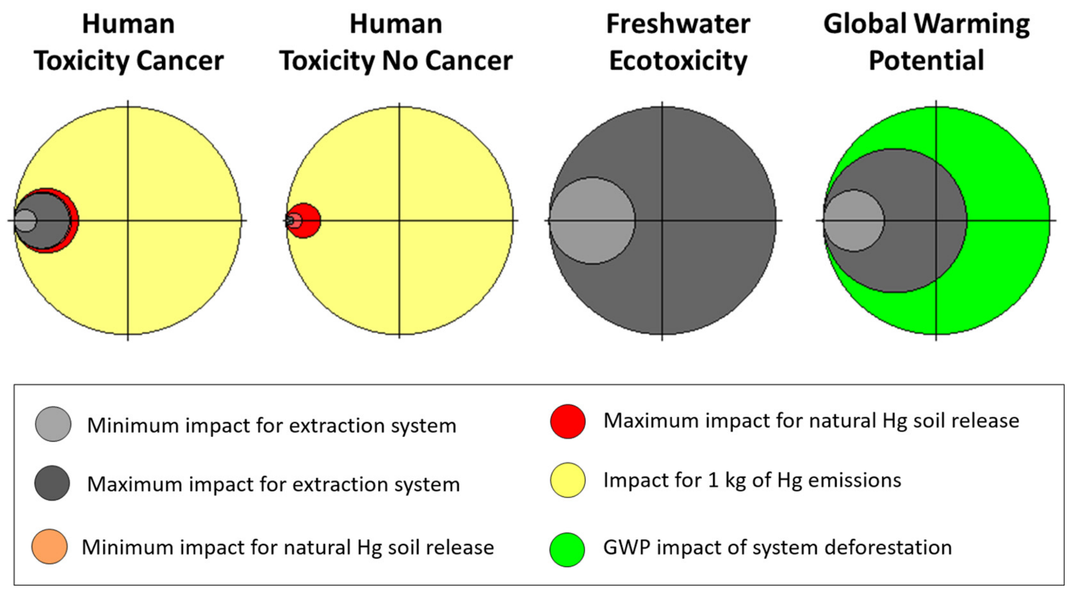

Fig. 5. LCA relative impacts between system extractions process and impacts for mercury emissions (both, direct systems emissions and potential mercury release from soil), considering 1 kg of mercury use for each kilogram of gold production.

characteristics found in MDD, being an extraordinary asset for biological resources (e.g. biodiversity) and global climate change (e.g. natural sequestration in rainforest). Thus, the difference in environmental impacts between the extraction systems studied needs to be considered when delineating public policy. However, an interpretation based on the sole assessment of one single impact category (e.g. climate change) is highly discouraged (Laurent et al., 2012). For example, when analyzing GHG emissions, extraction systems I and III present the lowest environmental impacts, but this trend is not preserved when expanding the analysis to human toxicity or freshwater ecotoxicity.

Moreover, based on the fate and transport of mercury, related impacts to the environment and human health are of multiple scales: local, regional and even global. Furthermore, deforestation portraits significant potential global environmental impacts, especially those linked to climate change and biodiversity loss. Interestingly, although human toxicity, freshwater ecotoxicity and climate change are frequently studied separately and do not necessarily show strong correlations between them, in this system a direct relationship between them was observed.

Unfortunately, actions taken in the past have not been successful in mitigating the serious environmental impacts related to alluvial mining activities. Instead, they have created a more damaging situation. For instance, illegal operations in "La Pampa" are a regrettable example of this. Despite the clear environmental degradation in the region, with regional and global implications (e.g. mercury atmospheric emissions and climate change), and growing deforestation and mercury contamination, any solution that has as its main focus the eradication of mining activities in MDD will not prevail. It is well understood that the exclusive use of "command and control" policies are not effective in developing countries, especially in areas which are prone to high corruption (Transparency International, n.d.), lack of efficient law enforcement due to the cultural imperative, as well as the inherent difficulty of enforcement in a very low density area and a highly centralized nation. For example, restricting the use of mercury has not limited its use in amalgamation processes nor promoted the use of retorts or other technologies. Moreover, researchers have failed to adopt measures to mitigate the impacts due to mercury use, particularly when attempting to expand the use of retort (Hilson, 2006). In addition, controlling the supply of diesel in mining activities or interdictions have not stopped or decreased these activities. Policy makers need to rethink the strategies and introduce innovative clean technology for gold extraction and introduce the social and economic dimensions into the discussion, the ones that also need to embrace the surrounding Andean communities. Also, the special characteristics of ASGM, if compared to large-scale mining, as well as the lack of data that portraits the region, need to be recognized by the government before the development of strategies (Damonte, 2016). In fact, mining activities, which represent most of the economic activity in the region, have an important influence in all spheres of society. A proof of this is the fact that MDD has become the second region, after Lima, with highest GDP per capita. Interestingly, when one observes dietary patterns, monetary wealth contrasts with the lowest consumption of fruit per capita in the nation (3.7 days per week that people in MDD eat fruit), and the highest obesity rate of the nation – 42% (INEI, 2015). These dietary results, when analyzed based on the total dietary intake, show a situation in which one of the highest caloric intakes in the nation is essentially based on a high consumption of red meat, cereals and sugar-based products (i.e. mainly soda). This leads to the highest GHG emissions per capita per year (i.e. 1.77 t CO_2eq) in the nation, as reported by Vázquez-Rowe et al. (2017).

Alluvial mining activities in the studied area are lucrative, have strong economic incentives and generate direct and indirect (e.g. terrestrial and fluvial transportation, maintenance services, etc.) employment opportunities that attract people from all around Peru, especially from the surrounding Andes, where there is a severe lack of employment opportunities (Arriarán and Chávez, 2017). A solution package that does not acknowledge this and expands their action plan to the Peruvian Andes (e.g. the generation of employment opportunities in those areas) would, once again, fail.

Fortunately, there are some initiatives performed by researchers and miners that offer tangible solutions to important problems. Reforestation on former mining sites has been initiated, in the form of pilot studies, by the CINCIA research group (Román-Dañobeytia et al., 2015). As of September 2018, 9 sites affected by mining activities have sheltered reforestation pilot studies (France Cabanillas, personal communication, 2018). If included in the LCA system boundary, these actions could revert some of the environmental impacts, namely climate change, related to ASGM activities in MDD. In addition, the use of gravimetric tables has been adopted by some miners, avoiding the need of the amalgamation process and mercury. While this technology is not a possibility for all extraction systems (e.g. type I or II extraction systems), due economic and site-specific limitations, pollution prevention strategies

could offer the possibility of centralized gold recovery facilities that use gravimetric tables instead of mercury. There may be some obstacles related to the adoption of this strategy, inherent to the characteristics of the extraction systems (e.g. location), but the main advantage is its higher gold recovery rate and significantly lower (i.e. more than 90%) human health impacts, as calculated in this research.

The inherent complexity of this socio-technological system demands a careful attention of all the affected dimensions. While this study mainly focuses on the environmental problems related to ASGM in MDD, it is imperative to analyze the social, cultural and economic dimensions before advocating for a partial solution. Clearly, there is no one solution for the alluvial mining system in MDD, but a set of integrated creative solutions that include all its dimensions. Results from this holistic strategy will not only be aligned with Sustainable Development Goals – SDGs 12 (i.e. responsible production and consumption) and 13 (i.e., climate action), but indirectly with others, such as SDG 8 (i.e. decent work and economic growth).

5. Conclusions

Human toxicity, freshwater ecotoxicity and climate change associated to alluvial gold mining in the Peruvian Amazon rainforest have been analyzed using a life cycle perspective. Results indicate that, regardless of the gold extraction system, mercury emissions related to gold recovery are, by far, the most important aspect triggering human toxicity, but that substantial reductions can be obtained if retort or gravimetric tables are used. In addition, depending on the extraction system, deforestation may have a major contribution to the system's GHG emissions.

The present study contributes to reduce the knowledge gap related to the environmental burdens of ASGM due to deforestation and mercury use. It also highlights the difference between the extraction systems of alluvial gold in terms of toxicity and climate change, as well as the role of natural mercury release to water streams due to soil removal. All these points are relevant due to the fact that current public policies do not distinguish between the different extraction systems and their environmental impacts.

Alluvial gold mining in MDD is also responsible for social and economic impacts. The regional GDP in MDD is highly dependent on gold mining and contributes, directly or indirectly, to employment opportunities. In fact, in 2012, it represented ca. 40% of the regional GDP (Chique et al., 2013). However, there are important negative socioeconomic outcomes from these activities, such as, human trafficking for labor or sexual exploitation, laundering, exploitation of minors, malnutrition, organized crime, insecurity, among others (Salo et al., 2016; Salo et al., 2015). Moreover, mining activities represent a latent risk to the thriving ecotourism industry in national parks throughout MDD and other regions of the Peruvian Amazon (Langeland, 2015).

The complexity of this sociotechnical system, grasping miners, social disparity in the region, and inefficiency of the central and regional governments allow these activities to rapidly expand their boundaries to restricted areas, such as natural reserves and parks. Future research and policy strategies should focus on a comprehensive understanding of the system and actions that take into account a wider range of sustainability dimensions, such as the social, cultural, economic, or institutional aspects.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.01.246.

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